DIGITAL LOW DROP-OUT VOLTAGE CONTROLLER INCLUDING EMBEDDED DUAL-LOOP FEEDBACK FOR MINIMUM ENERGY POINT OPERATION

TECHNICAL FIELD

[0001] Embodiments described herein pertain to power management in electronic systems. Some embodiments relate to voltage controllers.

BACKGROUND

[0002] Many electronic devices or systems, such as computers, tablets, and cellular phones, have a power management unit to control power supply voltage for some circuits (e.g., digital circuits) in the device or system. Conventional techniques are available to enable such circuits to operate at a minimum energy point (MEP). The MEP is the power supply voltage at which the circuit may consume the lowest energy per operation. However, as described in more detail below, some conventional techniques may have drawbacks that may make them unsuitable for some applications.

BRIEF DESCRIPTION OF THE DRAWINGS

[0003] FIG. **1** shows an apparatus including a voltage controller and a load, according to some embodiments described herein.

[0004] FIG. **2** shows example waveforms for the voltage controller of FIG. **1**, according to some embodiments described herein.

[0005] FIG. **3** shows a power switching unit of the voltage controller FIG. **1**, the load of FIG. **1**, and some values used in calculating average energy per operation, according to some embodiments described herein.

[0006] FIG. **4** is a block diagram showing a digital energy monitor, according to some embodiments described herein.

[0007] FIG. **5** shows a decision logic and a reference voltage generator of the voltage controller of FIG. **1**, and an example of finding the MEP in the voltage controller and the load of FIG. **1**, according to some embodiments described herein.

[0008] FIG. **6** is a flow diagram showing a method of determining MEP in a voltage controller and a load, according to some embodiments described herein.

DETAILED DESCRIPTION

[0009] As an operating voltage (e.g., supply voltage) of digital circuits scales down below a threshold voltage (Vth), the leakage energy consumed per operation in such digital circuit may start to increase exponentially while the active energy may decease quadratically. Hence, the total energy consumption may be minimized at a certain voltage value where the leakage energy becomes comparable to the active energy. Such a voltage value may correspond to the lowest point (e.g. a minimum energy point) on a curve that represents a relationship between operating voltage and energy consumption. Operating at the MEP in a particular digital circuit makes that particular digital circuit more energy efficient. The MEP varies depending on operating conditions such as workload, temperature, and Vth variations. For example, a workload with higher switching activities may lead to a lower MEP, because higher switching activities may dissipate more active energy without adding to any leakage energy.

[0010] Conventional techniques for finding the MEP at a given operating condition are proposed. However, some conventional techniques may have drawbacks. For example, some conventional techniques for finding MEP may use analog circuit components such as a time based analog-to-digital converter (ADC), a low-offset comparator, or other analog circuitry. Some of these techniques measure a small difference (ΔV) in values of an output voltage used in calculation for finding energy consumption per operation of a particular digital circuit. However, analog circuits used in these techniques may not be synthesizable. Therefore custom design efforts may be needed.

[0011] In another example, some conventional techniques may use a sizable off-chip capacitor to minimize the voltage difference (ΔV), because significant voltage drop may incur functionality issues at near-threshold voltage operation. Such an off-chip capacitor may result in board-level area and cost overheads.

[0012] Some conventional techniques for finding MEP may track the MEP of a load circuit only. That means that they may not consider the energy overhead of voltage controllers used for dynamic MEP operation. Thus, if the energy loss of voltage controllers is not negligible, the MEP of an entire system (e.g., a load circuit and a voltage controller) may be different from the tracked MEP of only a load circuit. This may result in inefficient MEP tracking.

[0013] Other conventional techniques for finding MEP may not provide in-situ (e.g., embedded) MEP tracking capability. That means that they may not dynamically track the MEP without knowledge of workload characteristics. Even if dynamic MEP tracking can be performed in conventional techniques, such techniques my need advanced knowledge of all possible workload conditions. Therefore sizable lookup tables may be needed. In some situations, software-level support may reduce such sizable lookup tables. However, a software solution may be inapplicable for dynamic MEP tracking in some devices or systems because such a solution may cause operational delay (e.g., delay in a path from hardware to software and then back to hardware).

[0014] The following description describes an apparatus (e.g., device or system) including a digital voltage controller to provide a supply voltage to a load. The voltage controller can include components (e.g., digital circuitry and logic) to perform improved techniques for tracking and finding the MEP in not only the load, but also the voltage controller.

[0015] The improved techniques for tracking and finding the MEP described herein may be fully synthesizable, may enable dynamic MEP tracking without advanced knowledge of workload characteristics of the load, may track the MEP of an entire apparatus or system (e.g., the MEP of the voltage controller and the load). The techniques described herein include components that can be embedded in the voltage controller (e.g., in a digital low drop-out (LDO) regulator). The techniques described herein may avoid an off-chip capacitor, thereby hardware overheads (e.g., power and circuit board area overheads) may be relatively smaller.

[0016] FIG. **1** shows an apparatus **100** including a voltage controller **110** and a load **115**, according to some embodiments described herein. Apparatus **100** can include or be included in an electronic device or system, such as a computer (e.g., desktop, laptop, or notebook), a tablet, a cellular phone, wearable electronics (e.g., smart watches), or other electronic devices or systems. As described in more